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# The evolution of European passenger car characteristics 2000–2010 and its effects on real-world $CO_2$ emissions and $CO_2$ reduction policy ☆

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H I G H L I G H T S

- ► We calculated the evolution of average European passenger car characteristics.
- ► Results of the calculation were used for predicting the real world $CO_2$ emissions.
- ► Reductions observed over certification are up to a point reflected in real world.
- ► The certification-real world emissions difference appears to increase in some cases.
- ► The gap between diesel and gasoline vehicle $CO_2$ emissions is narrowing.

A R T I C L E I N F O

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A B S T R A C T

The European passenger car certification test constitutes the basis for implementation and progress monitoring of the current $CO_2$ abatement policy. The certification test is performed over a single driving cycle, (New European Driving Cycle-NEDC). The dynamics of NEDC and the fact that it does not account for other factors results in $CO_2$ emissions which are non-representative of real-world performance. Using available data from the $CO_2$ monitoring database and literature and employing simple vehicle dynamics model and stochastic techniques, this paper attempts to calculate the average gasoline and diesel passenger car characteristics, investigate how the evolution of certain vehicle characteristics affects real world vehicle performance and to combine the above in order to evaluate the progress in terms of real world emissions and possible correction of existing emission factors. The analysis reveals that reductions over NEDC are generally reflected over real world. There were indications particularly for diesel vehicles that the NEDC—real world $CO_2$ emissions gap gradually widens and that existing emission factors should be amended accordingly. Currently this difference between certification and real world emission is estimated between 20 and 25%. The benefit of diesel vehicles compared to their gasoline equivalents in terms of $CO_2$ emissions appears to reduce.

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## 1. Introduction

European Union (EU) has made an independent commitment to achieve at least a 20% reduction of Greenhouse Gas (GHG) emissions by 2020 (compared to 1990 levels) irrespective of reductions achieved by other developed countries (EC, 2007). In order to live up to this commitment EU needs to tackle the increasing GHG emissions from the transport sector achieving decreases around 20% below their 2008 levels (EC, 2011). The share of transport in total emissions -including international transport- has reached 29% in 2008 compared to only 21% in 1990 (T&E, 2010). Passenger cars are responsible for some 12% of the GHG emitted in the EU (Clima, 2011).

Recognizing the importance of the passenger car contribution to the overall GHG emissions in Europe, EU adopted a series of policies and regulations in the past decade such as: car labelling for $CO_2$ emissions, the voluntary commitment of vehicle manufacturers to reach 120 g/km in 2012, regulations regarding emissions of light passenger and commercial vehicles and maybe most important the recent regulation 443/2009 (EU, 2009) which establishes mandatory limit (130 g $CO_2$/km on average) for newly registered passenger cars by 2015. In short, the cornerstone of European actions remained until 2009 the voluntary commitment of the car manufacturers to reduce the $CO_2$ emissions of their average passenger car, measure that had important and quantifiable results (Fontaras and Samaras, 2007) but failed to lead to the desired emission levels of 120 g/km. The new regulation

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(443/2009) follows the principle of an ''integrated approach'' setting a mandatory target of 130 g $CO_2$/km for 2015 and also foresees a 95 g/km limit for year 2020. In addition, it expects an extra 10 g $CO_2$/km to be delivered through other measures such as the use of biofuels. It is important to note that these policies resulted in a reduction of the average $CO_2$ emissions of 32 g $CO_2$/km between 2000 and 2010 (from 172 to approximately 140 g/km) (EEA, 2010).

However, future projections suggest increasing trends in road transport energy demand and $CO_2$ emissions. Although studies show that the growth of motorized transport activity in some industrial countries appears to decrease, the overall energy consumption continues to increase due to greater activity (Millard-Ball and Schipper, 2010). In the 2011 White Paper ''Towards a competitive and resource efficient transport system in Europe'', European Commission stresses that European transport is at a cross roads where old challenges remain and new have come. In the same document several different measures are proposed for reaching future targets. Amongst these there are regulatory measures such as appropriate standards for $CO_2$ emissions of vehicles in all modes and initiatives for ensuring that $CO_2$ and pollutant emissions are reduced under real world driving conditions -through a new test cycle- (EC, 2011).

The basis for implementation and progress monitoring of current policy is the European passenger car certification test. The test up to date is performed over a single driving cycle, the New European Driving Cycle (NEDC). The cycle has mild accelerations and decelerations and several steady state points. The dynamics of NEDC and the fact that it does not account for other factors such as the use of air conditioning, vehicle accessories, reduced tyre pressure etc, results in fuel consumption and $CO_2$ emissions which are non-representative of actual real-world performance. Various studies raise the issue of certification cycle's inadequacy to simulate actual vehicle performance (Van den Brink and Van Wee, 2001; Fontaras et al., 2007; Meyer and Wessely, 2009; Dings, 2010). In some cases quantifications of the shortfall between actual real world performance and the certified fuel consumption and $CO_2$ emissions are attempted. The difference between the two is generally estimated in the order of 15–20% (CEMT, 2005; Zallilnger and Hausberger, 2009; Keller et al., 2011).

This certification value to real world shortfall raises questions regarding the progress of EU commitments and the effectiveness of the measures adopted. How are the reported reductions translated under realistic operation and what is the actual effectiveness of the measures adopted so far? This paper attempts to address these questions using a simple vehicle modelling basis, data from the official monitoring database, literature sources and qualified assumptions. In this sense the scope of this paper is threefold, (a) attempt to extract information regarding the average gasoline and diesel passenger car characteristics in Europe, (b) investigate how the evolution of certain vehicle characteristics that reduce $CO_2$ emissions over the certification cycle affects real world performance and (c) combine the above in order to evaluate the progress in terms of real world emissions and possible correction of existing emission factors.

## 2. Methodology

The methodology used in this study is based on a simple vehicle dynamics—$CO_2$ emissions model, described below. Provided annual average values for the necessary vehicle parameters were available it would be relatively easy to reconstruct $CO_2$ emissions evolution over NEDC and attempt to predict those over any driving cycle using Eq. (1). However limited data are actually available. The current $CO_2$ monitoring mechanism in Europe (EEA, 2010) contains values regarding the weighed (by sales) average of $CO_2$ emissions, mass, engine capacity and engine power separately for Diesel, Gasoline and Alternative fuel vehicles. Data regarding aerodynamic characteristics and rolling resistance are measured for the certification procedure using coast-down tests but are not recorded and generally are very difficult to find. Other potentially useful data such as information regarding vehicle footprint and size only in 2010 started becoming available.

The model employed contains 4 basic parameters for which values are not available, aerodynamic resistance characteristics (AD), rolling resistance factor (rr), fuel consumption over idling and fuel cut off conditions (c) and average powertrain efficiency over the driving cycle (eff) -excluding idling and cut off conditions-. In order to estimate the evolution of these parameters in the 2000–2010 period over the certification test, two different approaches were used, a stochastic approach based on the application of random values for solving the $CO_2$ equations developed and an analytic approach. Both approaches are described in detail below. The results obtained from this analysis were later used to estimate the evolution of $CO_2$ emissions over more realistic driving conditions based on the driving profiles of the Artemis Driving cycles. It should be noted that in order to avoid problems related with the share of each technology in the fleet, which varies from year to year, the analysis addressed diesel and gasoline vehicles separately. An overview of the methodology is provided in Fig. 1.

### 2.1. Driving cycle $CO_2$ emissions model

The main resistances simulated while performing a laboratory driven cycle are: aerodynamic resistances (Ra) and rolling resistances (Rr). In addition other internal resistances (Ro) also affect vehicle operation e.g., rotational losses, electric consumers etc. Inertia forces defined by vehicle mass are also simulated. The main differential equation describing vehicle dynamics over time on a chassis-dyno can be summarized to the following (Gillespie, 1992):

$$m \times \frac{d}{dt}u(t) = \mathrm{Ftrc}(t) - (\mathrm{Ra}(t) + \mathrm{Rr}(t) + \mathrm{Ro}(t))$$

where $m$ symbolizes vehicle mass, $u$ vehicle speed, Ftrc the traction force applied on the wheel and $t$ time. Traction force may be positive in case of steady state motion or acceleration, zero in case motoring forces equal resistances and negative in case braking is necessary (an additional braking force is then introduced). Only in the first case vehicle engine provides traction power. In the second and third case fuel cut-off usually occurs (when clutch is engaged) or engine falls to idle operation (disengaged clutch). The integral of these positive traction force points provides the total ''useful'' work (Wcyc) produced by the engine in order to run the driving cycle. Hence, considering simple aerodynamic and rolling resistance models and assuming a Ro equal to 5% which is a good approximation of the order of magnitude of such losses in an average passenger car, Wcyc is equal to the following:

$$\mathrm{Wcyc} = \frac{1}{2} \times \rho \times \mathrm{Cw} \times A \times \int u^3 \times dt + 9.81 \times m \times \mathrm{rr} \times \int u \times dt + 1.05 \times m \times \int \frac{du}{dt} \times u \times dt$$

where $u$ is vehicle speed, $\rho$ is the air density (approx 1.2 kg/m$^3$), Cw is the aerodynamic resistance coefficient, $A$ the frontal area of the vehicle, $m$ vehicle mass and rr the rolling resistance factor value. Since the vehicle velocity over time is predefined for a given driving profile, the $CO_2$ emitted throughout the cycle can be

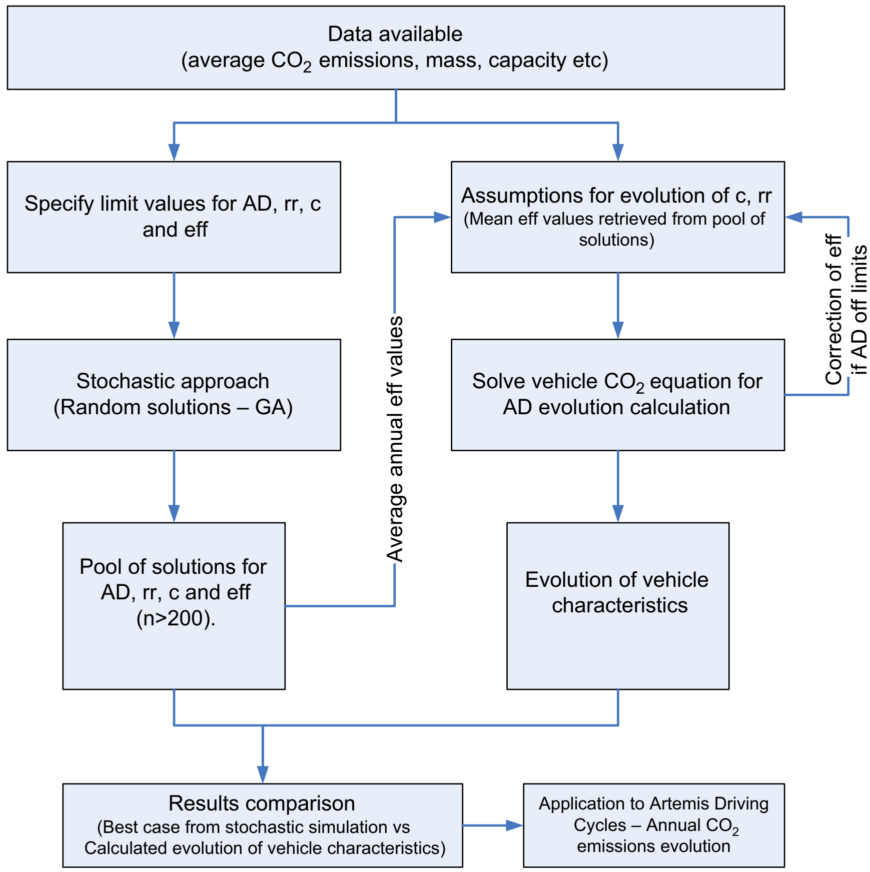


**Fig. 1.** Overview of the methodology. Left branch summarizes the steps of the stochastic approach while the right branch those of the analytical approach. Both approaches converge in the results comparison step.

approximated using the following equation.

$$CO_2 = q \times \left(\frac{1}{\text{eff} \times \text{Hu}} \times (Cw \times A \times K + m \times \text{rr} \times L + m \times M) + c\right) \quad (1)$$

where $q$ is a cycle-fuel specific conversion constant to g $CO_2$/km, eff is the average powertrain efficiency over the cycle, Hu is the heating value of the fuel used, $c$ expresses the sum of the fuel consumed over idling and fuel cut off conditions over the cycle and $K$, $L$ and $M$ are cycle specific constants. Such simplified models are also described and used in literature (Guzzella and Sciarretta, 2007; Keller et al., 2011).

For vehicles powered with the same fuel type, only the following factors are necessary for approximating their $CO_2$ emissions: Cw, $A$, $m$, rr, $c$ and eff. It is very difficult to decouple Cw and $A$ since their effect is combined. For this reason henceforward in the text a single aerodynamic drag factor (AD) will be used for aerodynamic resistances equalling the product of the two factors. It could be argued that factor c may not necessarily be present in the equation. The fuel consumed over idling conditions could as well be reflected through an overall lower average efficiency factor. However in the analysis we chose to distinguish $CO_2$ occurring from the two operating conditions for two reasons. The first was to allow the application of idling $CO_2$ emissions over cycles with different idling—cut off conditions/duration than NEDC and the second was to investigate whether changes of factor c occur through time, possibly reflecting technological advances such as engine start-stop.

### 2.2. Stochastic approach

As mentioned data regarding average vehicle mass and $CO_2$ emissions are available in Europe. AD and rr data from certification tests are not available. Total idle and cut off fuel consumption (c) is not recorded and probably only known to engine developers and vehicle manufacturers. Similarly average powertrain efficiency (eff) over positive traction conditions is very difficult to measure (if at all possible) since it is affected by several factors and reflects a global average of various powertrain working points. The first approach in estimating the aforementioned four parameters was through stochastically identifying solution of the equation. The equation solved, derived directly from Eq. (1), for each year $i$ and vehicle technology $t$ (gasoline/diesel) was the following:

$$\left| CO_{2i,t} - q_t \times \left(\frac{1}{\text{eff}_{i,t} \times \text{Hu}_t} \times (\text{AD}_{i,t} \times K + m_{i,t} \times \text{rr}_{i,t} \times L + m_{i,t} \times M) + c_{i,t}\right) \right| = 0 \quad (2)$$

**Table 1**
Limit values of the four unknown parameters.

| | | Gasoline | | Diesel | |
|---|---|---|---|---|---|
| | | Min | Max | Min | Max |
| AD ($Cw \times A$) | $m^2$ | 0.60 | 0.90 | 0.65 | 0.97 |
| rr | (–) | 0.0085 | 0.013 | 0.0085 | 0.013 |
| $c$ | (g) | 20 | 40 | 20 | 40 |
| eff | (–) | 0.13 | 0.3 | 0.15 | 0.35 |

Initially it was necessary to establish limit values for each of the unknown parameters as otherwise there may be infinite solutions that satisfy (2). The limits of the four parameters are presented in Table 1.

The following assumptions were adopted for establishing the limits.

For AD it was assumed that both gasoline and diesel vehicles present similar average aerodynamic drag coefficient (Cw) no bigger than 0.4 and no less than 0.27. In addition diesel cars present approximately 7% higher frontal area than gasoline ones ( according to EEA (2010) the average frontal width x height value of a gasoline vehicle in Europe was about 2.2 $m^2$ whereas for a diesel one was about 2.4 $m^2$). The limits presented in Table 1 are the product of the limits of these two parameters. Generally AD values for average vehicles are considered to be between 0.7 and 0.75 (Guzzella and Sciarretta, 2007).

Regarding rr equal limit values were considered for each technology since there is no direct link between tyres and engine technology. However it should be noted that tyre characteristics are associated to vehicle mass and engine power. The choice of values was based on a series of literature sources reporting measurements of tyre rr over the 2000–2010 period (Reithmaier and Salzinger, 2003; TRB, 2006; EC, 2008; EPEC, 2008; Evans et al., 2009; Vidal, 2010). Generally the average value of rr for new cars within the past decade is reported to be in the order or 0.0115 with replacement tyres showing relatively higher values. Nonetheless important progress was expected in the last 2 years following the European regulation on energy labelling of tyres and therefore a more optimistic lower end (0.00865) was chosen.

For value c very limited information is available. Indicative idling consumption values used previously (Fontaras and Samaras, 2010) for simulating 6 Euro 4 passenger cars were in the order of 0.1 g fuel/s and 0.12 g/s for gasoline and diesel passenger cars, respectively. Similar values are reported for older engines with capacity range between 1000 and 2000 $cm^3$ (Leung and Williams, 2000). Assuming a total time of 290 s during which the engine of an average sized car operates at idle (or moving with clutch disengaged) over NEDC, a working number value of c would be 29 g and 34.8 g for gasoline and diesel cars, respectively. Since in this case there is a wide margin for uncertainty it was decided to extend the maximum and minimum limits to 20 and 40 g of fuel over NEDC.

A relatively wide range of average powertrain efficiency was also considered for both technologies starting from relatively low values (0.13 and 0.15) and reaching up to 0.3 and 0.35 close to the reported maximum engine efficiency values for light duty gasoline and diesel engines, respectively.

A random number generator function was used in Matlab for creating uniform distributions of random values for each parameter within the maximum and minimum limits specified. For parameters AD, rr and *c* 200 different random values were used. The solution is sensitive to eff and for this reason 200 random values were considered. Using iteration loops all possible combinations of values ($25 \times 10^6$) were employed in (2) and the 200 combinations that gave the best results in terms of absolute error were kept as possible alternative solutions. A statistical analysis followed.

A similar effort was performed in parallel using Matlab's optimization toolbox. A genetic algorithm (GA) was employed for optimizing fitness function (2). Default values were used for most attributes, the population size was set to 100, crossover fraction was set to 0.9 and stochastic-uniform selection function was used. The genetic algorithm was run for at least 30 times per year-engine technology providing pools of possible combinations.

Statistical analysis of the results showed that the solutions provided in both cases presented the same characteristics. In this paper only the results of the stochastic approach will be used as more sets of solutions were retrieved from this approach.

### 2.3. Analytical solution

In addition to the stochastic approach an analytical solution of function (2) was attempted based on a series of qualified assumptions regarding the evolution of rr, c and eff between 2000 and 2010 which are presented below in detail. Eq. (1) was then solved with respect to AD and the evolution of AD was calculated.

*Evolution of rolling resistance (rr) values:* A short literature review on the evolution of tyre rolling resistance values indicated that progresses in rolling resistance have been recorded during the past 30 years. Michelin in 2010 reported reductions in their tyres' rolling resistance values of 7% between 2003 and 2008 ie approximately 1.4% per year. (Vidal, 2010). Average annual reductions between 1990 and 2000 in the order of 1% are also reported in other sources (Van den Brink and Van Wee, 2001; CEMT, 2005). The impact assessment study performed for the European Commission supporting the tyre labelling regulation introduction reports an average summer tyre rolling resistance of 0.0118 for year 2004 (accounting for both original equipment and replacement tyres). The equivalent value for winter tyres was 0.0128 (EPEC, 2008). For year 2003 Michelin has reported rolling resistance values of 0.0102 for their tyres, while TUV automotive measured in the same year rolling resistance values of 0.0116 on average over a pool of tyres found in the market (Reithmaier and Salzinger, 2003). Similar trends but slightly lower rolling resistance values possibly due to different tyre sizes and measurement standards are reported for the US market (Evans, et al., 2009). Regarding the dependency of rolling resistance to vehicle size a trend towards lower rolling resistance values with the increase of tyre diameter is mentioned (T&E, 2007; EPEC, 2008). Although this does not directly link rolling resistance to vehicle mass, it is expected that bigger and heavier vehicle models (e.g., SUV) probably present lower rolling resistances due to bigger rim diameters.

In view of the above, tyre rolling resistance evolution was estimated as follows. A fixed rolling resistance value of 0.0115 for year 2004 was assumed for both diesel and gasoline vehicles. Although diesel vehicles are heavier than gasoline vehicles it was impossible to find data regarding the average rolling resistance of each vehicle category. In addition part of the difference in mass originates from the heavier powertrain system and does not necessarily correspond to differences in the size of tyre rims. A fixed rr reduction rate of 1% and 1.5% per year was adopted for the period prior and after 2004, respectively, reflecting the standard improvement rate in the first case and the increased effort to reduce rolling resistance in the recent past claimed by the manufacturers (Smokers et al., 2006) in the second case. It was assumed also that annual changes in vehicle mass should be also reflected in rolling resistance values through a reverse proportional relation. These assumptions resulted in the following model:

$$\mathrm{rr}_i = \mathrm{rr}_{i-1} \times a \times m_{i-1}/m_i$$

where $\mathrm{rr}_i$ is average rolling resistance in year *i*, a is the improvement factor (0.99 prior to 2004 and 0.985 after 2004) and $m_i$ average vehicle mass in the respective year.

*Evolution of idling consumption (c) values.* In lack of detailed information regarding idling consumption over NEDC it was decided to link directly annual changes in the average idling fuel consumption to changes in average engine capacity. A clear linear relationship between fuel consumption and engine capacity is presented by Leung and Williams (2000) with higher capacities presenting higher consumptions. Factor c was taken equal to 30 g and 34.5 g of fuel for gasoline and diesel vehicles, respectively in year 2000. Knowing the annual average engine capacity (cap) data from the EU monitoring database the following equation was used to model the evolution of c over year *i*.

$$c_i = c_{i-1} \times \mathrm{cap}_i/\mathrm{cap}_{i-1}$$

*Average powertrain efficiency (eff) evolution.* It was not possible to retrieve average efficiency values from literature sources. Only limited indicative information regarding specific car models is available which should not be extrapolated to a global fleet average or one or several years. The stochastic simulation performed in the first step of the analysis revealed that in contrast to other parameters the values of eff calculated within the various groups of solutions followed a normal distribution with relatively small standard deviations (4.5–5.5%). It was assumed that since the number of solutions considered was large (about 300 for each year and vehicle technology) the mean value in each case possibly reflects the actual global average. These mean eff values were introduced as initial values that allowed the calculation of AD. After the calculation of AD a feedback loop slightly correcting eff was introduced in order to bring AD values within the predefined limits mentioned before, when needed.

## 3. Results

### 3.1. Stochastic approach

A pool of about 300 solutions was retrieved for each year and vehicle technology combination (in total 22 combinations). These solutions presented the lowest absolute error (absolute value of the difference between calculated $CO_2$ and reported $CO_2$) and individually could be potential solutions of Eq. (2). Statistical analysis of the groups of each characteristic revealed some interesting patterns. Fig. 2 presents indicative distributions of the results for gasoline vehicles and year 2003. As shown in subfigures b–d, the values calculated for AD, rr and c followed uniform distributions. On the other hand, eff followed a normal distribution (subfigure a). The picture was almost the same in all cases examined. AD, rr and *c* presented uniform distributions, their mean values and standard deviations were almost the same from year to year and only differentiated between vehicle technologies. Eff followed normal distributions, with mean values that varied between years and engine technologies and with coefficients of variation ranging from 4.5 to 5.5%. The normality of the distributions of eff was validated through a chi-square goodness-of-fit test for discrete or continuous distributions in Matlab. In 18 out of 22 cases the test confirmed the null hypothesis of normality on a 95% confidence interval. Fig. 3 summarizes the results of calculated eff for gasoline (a) and diesel (b) vehicles from 2000 to 2010. ).

Based on the fact that eff results consistently followed normal distributions with low coefficients of variation it was assumed that the average value of the results could be accepted as the actual value of eff and be used as such in the analytical approach.

In an effort to further elaborate on the results, all sets of solutions containing eff values close ($\pm$1.5%) to the average eff value were isolated and studied individually. However, even in the case of these subgroups of the original sample, AD, rr and *c* maintained the same distribution characteristics and average values. It is interesting to mention that the results of the stochastic approach through genetic algorithms also presented similar characteristics. Although in that case the groups of results were much smaller the distributions observed were the same and with similar mean values.

Finally in addition to the statistical analysis, the best case results (lowest error solutions) were also used in the analysis as optimal solutions of Eq. 2 (see Table 2).

### 3.2. Analytical approach

The results for the vehicle average characteristics which were calculated through the analytical approach are summarized in Table 3and Table 4. The annual evolution of the vehicle characteristics

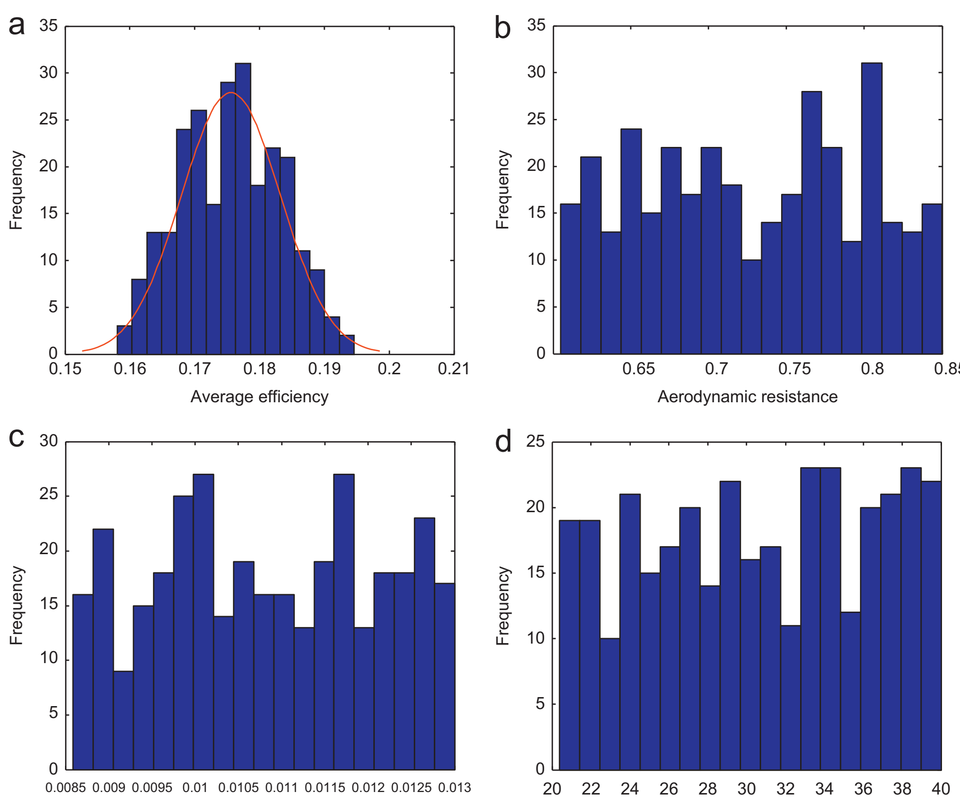


**Fig. 2.** Distributions of the results for eff (a), AD(b), rr (c) and *c* (d).

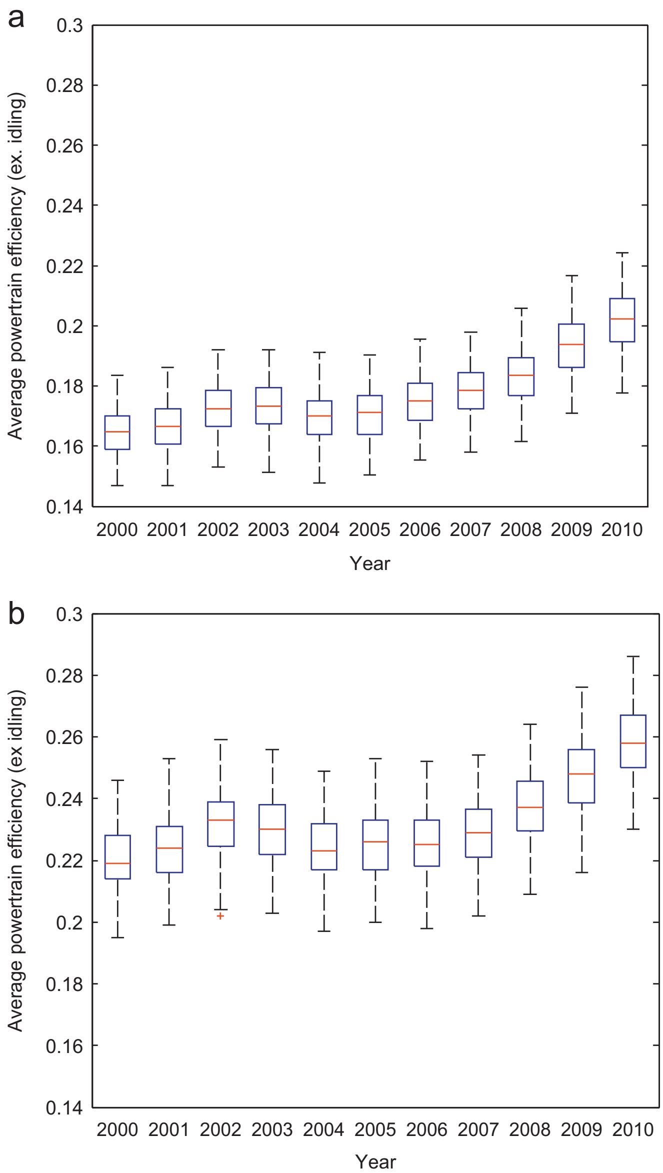


**Fig. 3.** Summary of the eff calculation results for gasoline (a) and diesel vehicles (b). In each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme datapoints, and the outliers are plotted as crosses.

**Table 2**
Solutions that gave the least error (best) for each year-vehicle type.

| | Gasoline | | | | Diesel | | | |
|---|---|---|---|---|---|---|---|---|
| | AD | rr | *c* | eff | AD | rr | *c* | eff |
| 2000 | 0.69 | 0.0105 | 39.2 | 0.162 | 0.75 | 0.0122 | 39.2 | 0.235 |
| 2001 | 0.63 | 0.0121 | 23.2 | 0.164 | 0.64 | 0.0123 | 39.2 | 0.229 |
| 2002 | 0.77 | 0.0120 | 25.2 | 0.179 | 0.68 | 0.0130 | 32.8 | 0.242 |
| 2003 | 0.64 | 0.0118 | 23.6 | 0.168 | 0.76 | 0.0129 | 32.0 | 0.246 |
| 2004 | 0.83 | 0.0107 | 39.6 | 0.180 | 0.73 | 0.0104 | 23.6 | 0.219 |
| 2005 | 0.73 | 0.0117 | 25.2 | 0.174 | 0.82 | 0.0127 | 23.6 | 0.243 |
| 2006 | 0.82 | 0.0086 | 28.4 | 0.172 | 0.84 | 0.0100 | 26.4 | 0.230 |
| 2007 | 0.70 | 0.0090 | 25.2 | 0.166 | 0.69 | 0.0120 | 32.4 | 0.233 |
| 2008 | 0.77 | 0.0110 | 24.0 | 0.186 | 0.62 | 0.0098 | 38.0 | 0.223 |
| 2009 | 0.60 | 0.0104 | 33.6 | 0.181 | 0.78 | 0.0113 | 28.8 | 0.254 |
| 2010 | 0.79 | 0.0112 | 27.6 | 0.208 | 0.76 | 0.0108 | 27.6 | 0.260 |

was used to reconstruct average NEDC emissions based on the functions described by Fontaras and Samaras (2010) that link improvements in vehicle characteristics to $CO_2$ reductions. As shown in the tables, in most cases predicted emissions are within $\pm 0.7\%$ of the target (official) values suggesting that the evolution of characteristics calculated in the analytical approach is realistic and well combined with a vehicle simulation based methodology.

However the aim of the study was primarily to identify trends in vehicle characteristics that are of relevance to $CO_2$ emissions rather than calculate sets of their absolute values. In order to better understand and cross validate the trends presented above, the results of the analytical approach are presented together with those of the best case solution obtained from the stochastic approach in Fig. 4 and Fig. 5.

Starting from average powertrain efficiency (eff) we observe in the case of gasoline vehicles (subfigure a) continuous increases that slightly accelerate after year 2008. The data of the analytical solution coincide very well with those the best case of the stochastic approach that present the same trends and approximately the same absolute values. It appears that the efficiency of gasoline vehicle powertrains progressively improved by about 22% during the past decade. It also seems that the introduction of downsized engines and other fuel efficient technologies after 2007 accelerates the improvement rate. In the case of diesel vehicles (subfigure b) the picture is slightly different. The analytical solution shows stagnation in average diesel powertrain efficiency between 2000 and 2007. However a notable improvement rate appears since 2007 and the overall increase throughout the decade reaches 10%, an important figure but much less impressive than that of gasoline powertrains. The best case solution shows again an equal improvement within the decade but annual values fluctuate significantly from year to year. In addition eff values tend to be slightly higher compared to those of the analytical solution. However even in this case eff values of 2000 and 2001 are almost equal to those of 2006 and 2007 and significantly increase after year 2008. Meyer and Wessely (2009) report improvements in thermodynamic efficiency indicators of passenger cars between 2000 and 2007 that match the values found in this study for both diesel and gasoline powertrains. An average annual improvement of 0.9% in diesel was also reported by Zachariadis (2006).

It should be noted that current certification test in Europe allows for a series of flexibilities that affect the reported $CO_2$ emission levels of cars. These flexibilities can lead to measurable $CO_2$ benefits (Kadijk et al., 2012). The analysis performed cannot compensate for such flexibilities. Therefore any potential gaming from the side of manufacturers is reflected as improvements in mainly average powertrain efficiency of the vehicles. This might lead to offsets in the average efficiency calculated. The overall trends presented however are expected to be accurate.

In Fig. 5 (subfigures a and b) results regarding AD are presented. For both types of vehicles the results of the analytical approach exhibit approximately the same constant evolution with time. Mean values are slightly higher (0.75 compared to 0.72) in the case of diesel vehicles as expected because of their bigger size (as mentioned diesel vehicles in 2010 presented about 7% higher frontal area). In all cases an important drop of AD value appears for years 2002–2003 which can be associated with the extreme average vehicle mass values recorded for the same years. It is likely that such increases in mass are due to miscalculations or errors in the monitoring database. The mass values reported for these years need to be reviewed and if necessary revised. The best case results for AD show a slightly different trend with AD increasing on average throughout the decade. However, results for both gasoline and diesel cars are widely scattered and their average linear trendline lies quite close to the results of the analytical approach.

Overall it is assumed that throughout the past decade only limited differentiations must have occurred in average aerodynamic resistances. This does not necessarily mean that the aerodynamics of the

**Table 3**
Results of analytical approach for gasoline vehicles.

| Year | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reported $CO_2$ (g/km) | 177.4 | 175.3 | 173.5 | 171.7 | 170.0 | 168.1 | 164.9 | 161.6 | 156.6 | 147.6 | 142.6 |
| Reported average mass (kg) | 1264 | 1283 | 1306 | 1294 | 1237 | 1235 | 1238 | 1235 | 1228 | 1206 | 1216 |
| rr | 0.0117 | 0.0116 | 0.0116 | 0.0117 | 0.0115 | 0.0113 | 0.0111 | 0.0110 | 0.0109 | 0.0109 | 0.0107 |
| AD | 0.68 | 0.66 | 0.64 | 0.65 | 0.71 | 0.72 | 0.71 | 0.72 | 0.72 | 0.71 | 0.71 |
| c (g of fuel) | 30.0 | 30.0 | 30.2 | 30.2 | 30.2 | 30.2 | 30.0 | 29.9 | 29.4 | 27.9 | 27.9 |
| Corrected eff | 0.164 | 0.166 | 0.168 | 0.170 | 0.171 | 0.173 | 0.175 | 0.178 | 0.183 | 0.191 | 0.198 |
| Predicted $CO_2$ (g/km) based on Fontaras and Samaras (2010) | | 175.6 | 173.8 | 171.6 | 170.6 | 168.2 | 165.4 | 161.6 | 155.7 | 145.7 | 142.4 |
| Difference | | 0.2% | 0.2% | −0.1% | 0.4% | 0.0% | 0.3% | 0.0% | −0.6% | −1.3% | −0.2% |

**Table 4**
Results of analytical approach for diesel vehicles.

| Year | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reported $CO_2$ (g/km) | 160.3 | 159.7 | 158.1 | 157.7 | 156.2 | 156.5 | 157.9 | 156.3 | 151.2 | 145.3 | 139.3 |
| Reported average mass (kg) | 1488 | 1519 | 1564 | 1536 | 1463 | 1479 | 1501 | 1510 | 1508 | 1498 | 1507 |
| rr | 0.0115 | 0.0114 | 0.0116 | 0.0118 | 0.0115 | 0.0112 | 0.0109 | 0.0108 | 0.0107 | 0.0106 | 0.0105 |
| AD | 0.79 | 0.75 | 0.68 | 0.69 | 0.77 | 0.76 | 0.76 | 0.76 | 0.75 | 0.75 | 0.72 |
| c (g of fuel) | 34.0 | 33.7 | 33.3 | 33.1 | 32.3 | 32.0 | 32.0 | 32.1 | 31.7 | 31.1 | 30.7 |
| Corrected eff | 0.228 | 0.228 | 0.229 | 0.229 | 0.229 | 0.227 | 0.226 | 0.228 | 0.235 | 0.243 | 0.251 |
| Predicted $CO_2$ (g/km) based on Fontaras and Samaras (2010) | | 159.3 | 157.9 | 157.4 | 155.3 | 156.6 | 157.1 | 156.9 | 150.4 | 144.2 | 139.3 |
| Difference | | −0.3% | −0.1% | −0.2% | −0.6% | 0.1% | −0.5% | 0.4% | −0.5% | −0.7% | 0.0% |

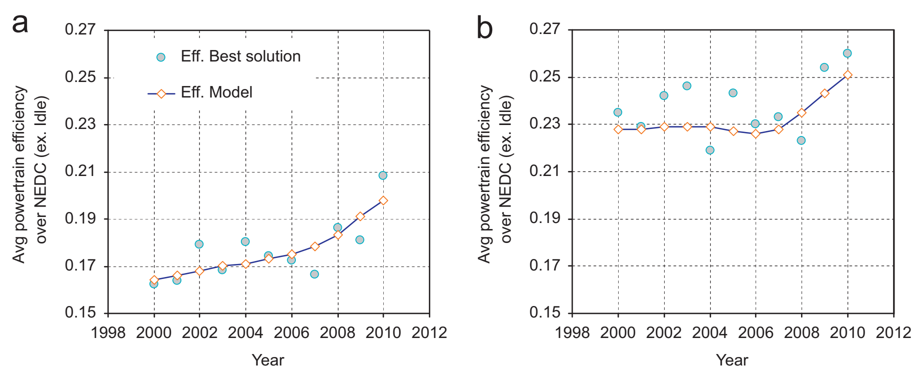


**Fig. 4.** Evolution of eff for gasoline (a) and diesel (b) vehicles.

vehicles have not improved but rather that average size increases probably canceled out improvements in aerodynamics of the vehicles. It is also likely that the introduction of small size vehicles may not directly improve aerodynamic characteristics of the fleet as smaller cube-shaped cars tend to have a higher aerodynamic drag coefficient which cancels out part of their reduced size benefit. Experimental data are necessary in order to better understand how the aerodynamic characteristics of the passenger car fleet have evolved in the past decade.

Results regarding rolling resistance evolution are presented in Fig. 5 (subfigures c and d). In the case of the analytical approach, rr values were imposed based on the model and the justification presented in Section 2. For gasoline vehicles the best case results lay close to those of the model, with their linear trendline showing almost the same slope but exhibiting slightly lower absolute values. For diesel cars best solution values lay on both sides of the rr model with a wider scatter. Their linear trendline almost coincides with the rr model having again approximately the same slope but relatively higher absolute values. The trends reported in literature were accurately reflected in both cases showing reductions of about 12% in average rr between 2000 and 2010. The absolute value differences in the best case solutions possibly indicate that the assumption of equal rolling resistance between gasoline and diesel vehicles needs to be amended towards higher values for diesel and lower for gasoline cars. Considering though the fairly limited difference no important impact on the overall result is expected.

Finally the data regarding idle consumption are summarized in subfigures *e* and *f*. The values of *c* in the analytical approach were calculated based on the model described in Section 2. Being coupled with average engine capacity, the value of *c* gradually decreases over time. For gasoline vehicles lower values were retrieved for most years in the best case solution but the linear trend line follows closely the analytic results, also showing a reduction trend with time. Similarly in the case of diesel the reduction trend is preserved at a slightly higher rate. However the values of both solutions seem to better coincide in the case of diesel than gasoline vehicles.

## 4. Discussion

The differences between the emissions measured over the certification test and those occurring during actual vehicle operation have raised important questions regarding the effectiveness of the current $CO_2$ reduction measures and policies. Results from various studies indicate that there is no guarantee that real world $CO_2$ emissions decrease when NEDC $CO_2$ emissions decrease. The impact may depend on the higher transience of real world driving, use of additional equipment not considered in the

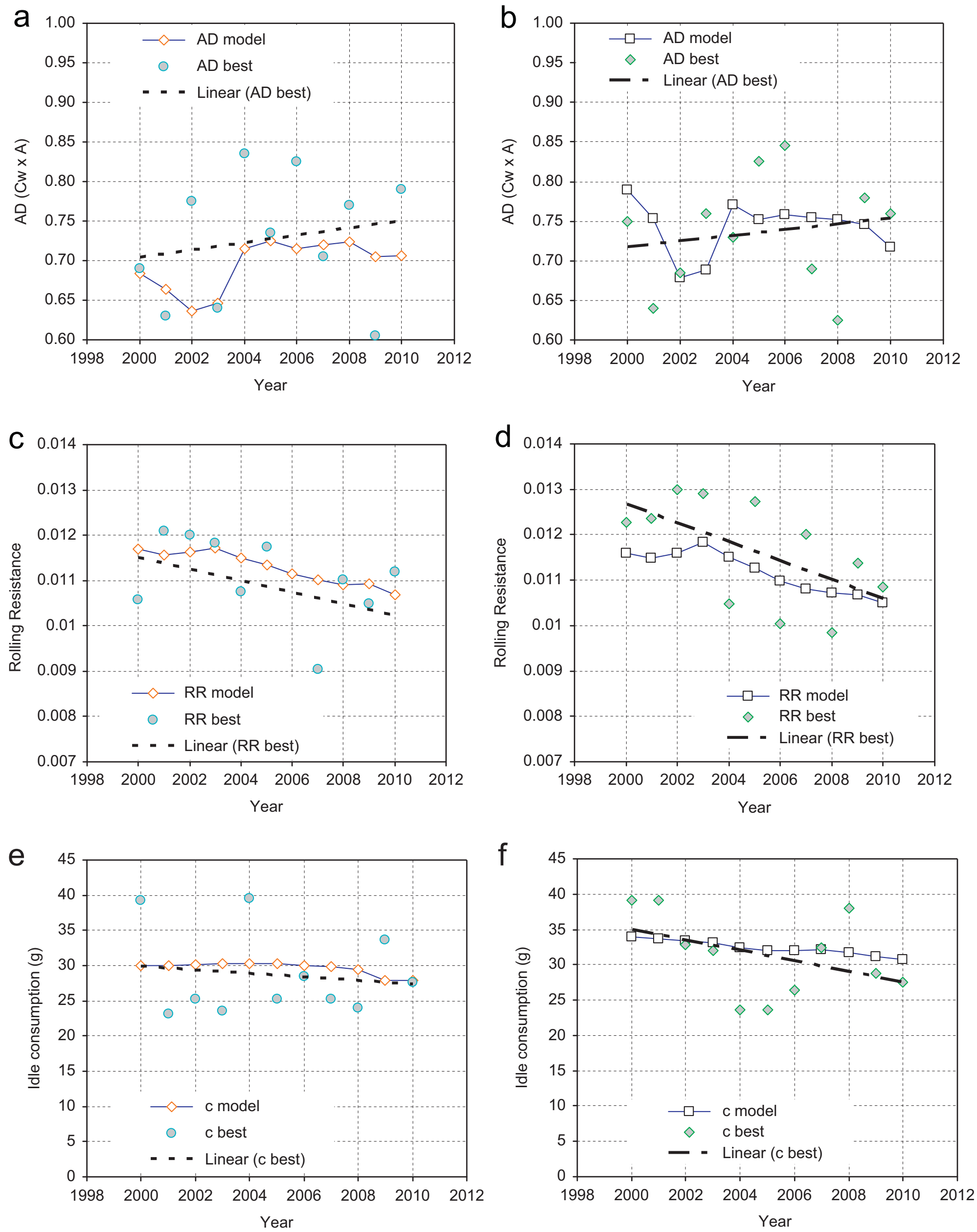


**Fig. 5.** Evolution of AD, rr and *c* for gasoline (a, c, e) and diesel (b, d, f) vehicles, respectively.

certification test (e.g., air conditioning etc) but also from the share between total urban, extra urban and motorway mileage (Zervas, 2010) and potential rebound effects (Schipper and Fulton, 2008), i.e., increases in $CO_2$ emissions caused by higher vehicle use resulting from the reduction in fuel costs due to lower fuel consumption. The basic tools currently used in Europe (COPERT, HBEFA) for assessing the real world $CO_2$ emissions of the passenger car fleet are based on emission factors derived from various experimental campaigns(Haan and Keller, 2004; Colberg et al., 2005; Ntziachristos et al., 2009). However it is very difficult to continuously generate enough experimental data for updating current emission factors to reflect the most recent evolutions. In this paragraph, the data regarding average vehicle characteristics calculated in the previous section were used for estimating the average vehicle performance over more realistic driving conditions. The same theoretical approach was adopted, but in this case the analysis was based on the Artemis cycles (Andre et al., 2006). For these calculations the same evolution of all vehicle characteristics as in NEDC was assumed. The absolute values of average powertrain efficiency were set for year 2000 so that the average $CO_2$ emissions during the 2000–2003 period over each of the Artemis cycles was equal to the average $CO_2$ emissions for the same time period and cycles recorded in the Artemis database. The same annual rate of change in average powertrain efficiency as in the case of NEDC was assumed for year 2004 and onwards.

The evolution of $CO_2$ emissions for an ”average” European passenger car over the three Artemis cycles is summarized in Fig. 6. A set of combined Artemis cycle data is also given. This set of data was calculated based on a 34% urban, 33% rural and 33% motorway mileage distribution (Fontaras and Samaras, 2007; Leduc et al., 2010; Keller, et al., 2011). It is observed that $CO_2$ emissions over all cycles present downward trends during the 2000–2010 period. For gasoline vehicles urban and rural emissions appear to decrease by approximately 20% and the motorway emissions by 17%. In the case of diesels, $CO_2$ improvement over urban conditions was in the order of 10% while over rural and

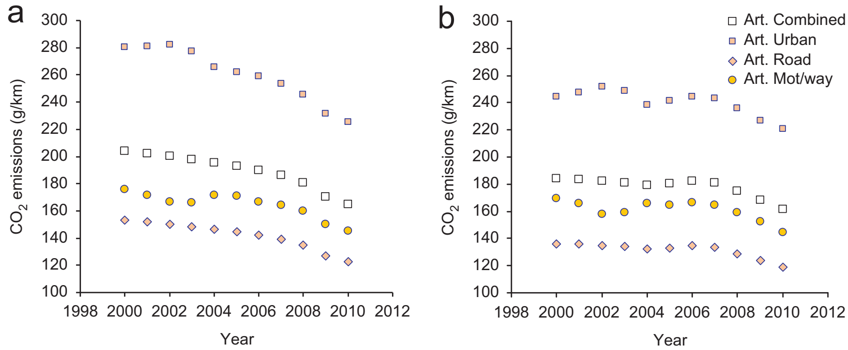


**Fig. 6.** Calculated evolution of $CO_2$ emissions over Artemis cycles for an average gasoline (a) and diesel (b) passenger car.

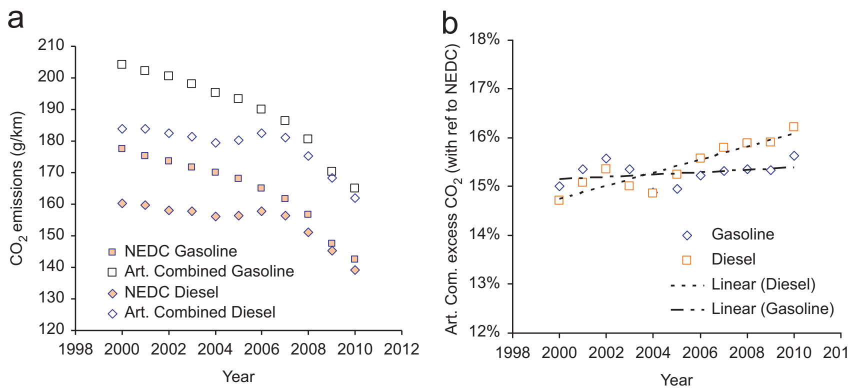


**Fig. 7.** Evolution of the Artemis combined $CO_2$ emission compared to the official (NEDC) reported data (a) and corresponding excess emissions of Artemis combined as a % of NEDC reported emissions (b).

motorway cycles reached 12 and 15%, respectively between 2000 and 2010 with most gains being achieved from 2007 and on.

Fig. 7(a) presents the annual $CO_2$ emissions over NEDC (reported values) and the calculated equivalent over Artemis combined conditions. On a first glance it appears that values of the combined Artemis cycle follow the same trends as the reported ones, having an offset of about 15% towards higher emission levels (subfigure b). It is interesting that this offset does not remain the same over the years but appears to increase particularly for diesel vehicles. This observation suggests that the difference between the certified fuel consumption of diesel passenger cars compared to their actual real world performance increases and that the improvements achieved over NEDC are not necessarily reflected over more realistic driving conditions. The offset for the gasoline cars remains very low and can be considered as constant.

Having calculated the evolution of $CO_2$ emissions over more realistic driving profiles an estimation of actual real world performance was attempted. The assumptions made for this calculation were the following. A 3% higher aerodynamic resistance was assumed in order to compensate at least for the higher air density due to lower average temperatures in Europe compared to those of the certification test (15 °C compared to at least 20 °C). A 10% higher rolling resistance value was considered, originating from replacement tyres, usage of winter tyres or lower tyre pressures than the nominal(Reithmaier and Salzinger, 2003; Smokers, et al., 2006; TRB, 2006; Barrand and Bokar, 2008). Regarding vehicle mass an increase of 100 kg was assumed to account for the weight of an extra passenger (in addition to the driver) and other equipment or luggage that might be loaded on the vehicle. Air conditioning was assumed to cause a 3% flat increase in emissions based on the findings of Leduc et al. (2010). Finally average powertrain efficiency was assumed to be 5% higher in order to reflect the effect of higher load engine operation.

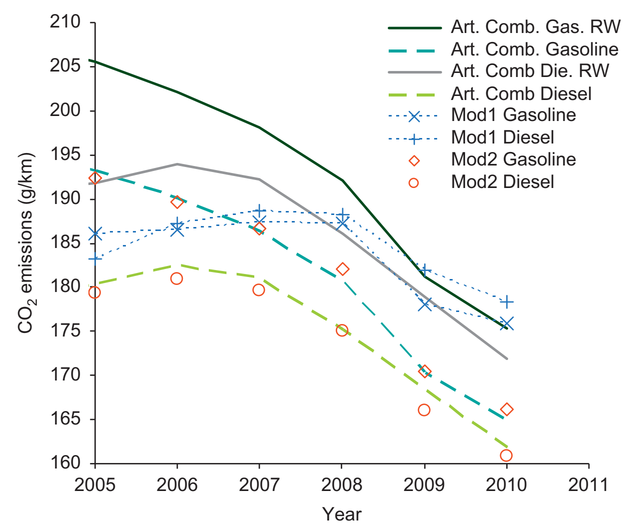


**Fig. 8.** Comparison of real world $CO_2$ emissions as calculated by the different models.

The results of this calculation for years 2005 to 2010 (summarized in Fig. 8 and Fig. 9) revealed real world (Art. comb. RW) operation excess emissions of 22–25% compared to certification. The latter are 7–10% higher than those calculated previously over the Artemis combined cycle. In this case diesel excess emissions still present increasing trends while gasoline excess emissions remain constant.

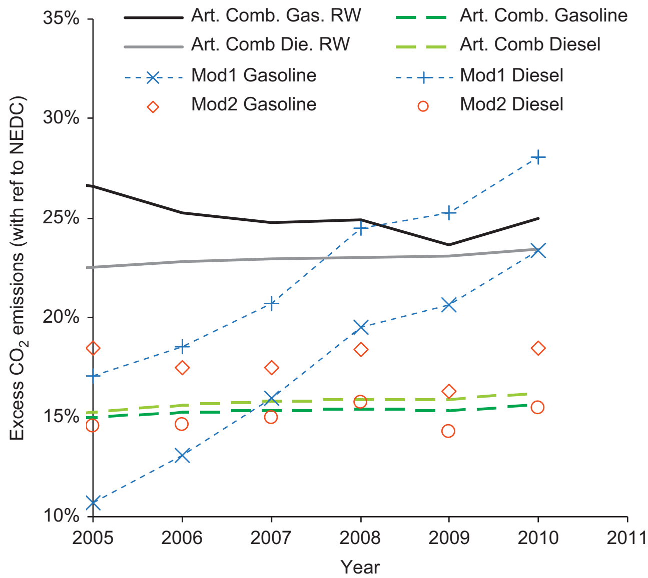


**Fig. 9.** Excess emissions with reference to NEDC values.

Real world $CO_2$ emissions are also compared against the equivalents calculated by 2 models (mod 1 and mod 2) developed by Keller et al. (2011). These models were produced through statistical analysis of several different databases containing data from real world vehicle usage and explicit measurements. These empirical models were constructed to check how well measured in-use fuel consumption of PCs can be predicted on the basis of independent variables. The models were built on the basis of linear combinations of the variables mass, engine capacity, rated power, and power to mass ratio. The models were first applied to all measured in-use fuel consumption data that became available to the developers. From in total 12 models tested, with different linear combinations of some or all of these variables, the best correlation coefficients (R2 ~0.9) were found for the models including mass, rated power (or engine capacity) and the type-approval $CO_2$ emissions. The models employed in this paper are part of a group of correction functions for $CO_2$ emissions to be introduced in HBEFA and COPERT emissions inventorying tools. The two models are:

$$CO_2 = 3.17 \times (a_1 + b_1 \times P_{\text{rated}} + c \times \text{AD} + e \times (rr + 18 \times \text{rr}_1) + d_1 \times m) \text{ (Mod.1)}$$

$$CO_2 = 3.17 \times (a_2 + b_2 \times TA\_\text{FC} + d_2 \times m) \text{ (Mod.2)}$$

where $CO_2$ are the real world $CO_2$ emissions [g/s], $P_{\text{rated}}$ is the average rated engine power [kW], m is the average vehicle mass [kg], AD is the aerodynamic drag and rr+18 $r_1$ is tyre rolling resistance at 18 km/h. Factors $a$, $b$, $c$, $d$, $e$ are constants calculated after applying regression formulas on the existing pool of data, different for diesel and gasoline passenger cars. Developers claim that these models tend to underestimate $CO_2$ emissions of older vehicle technologies and thus it was chosen to present results only for post 2004 vehicles.

As shown in Fig. 8 all calculations resulted in similar $CO_2$ evolution with time. Mod 2 matches almost exactly the values of Artemis combined emissions calculated in this study for both vehicle technologies and probably expresses a more realistic driving style compared to the certification test. Results of Mod 1 provided lower real world $CO_2$ emissions for years 2005–2007 but from 2008 and forward seem to coincide with the Artemis combined RW calculated $CO_2$, possibly expressing a better approximation of the in use vehicle emissions. The 2005–2007 are rather underestimated as they lay even lower than the values of Mod 2 in certain cases, being close to the Artemis combined diesel emission levels even for gasoline cars. As this analysis showed there is no evidence to justify increase in gasoline vehicle $CO_2$ emissions between 2005 and 2007.

All calculations show a convergence of $CO_2$ emissions between gasoline and diesel vehicles particularly after year 2008. The difference in fuel consumption between the two engine technologies is reduced to about 2.5% in favor of diesel compared to a range of up to 10–15% in the beginning of the decade. In fact mod 1 suggests that after 2006 real world emissions of diesel cars are higher than those of gasoline vehicles. It is difficult to accept that average diesel vehicles are emitting higher $CO_2$ under real world conditions on a g/km basis. Indications though suggest that the difference between the two engine types is almost negated. Generally diesel vehicles have a higher annual mileage (Schipper and Fulton, 2008; Leduc, et al., 2010) due to various reasons such as higher usage demand and lower vehicle running costs. It is thus possible that the introduction of a diesel vehicle in the fleet will, in the end, result in equivalent or even higher $CO_2$ and certainly higher $NO_x$ emissions as those of a similar gasoline one. This observation is important as for years the cornerstone measure for reducing vehicle $CO_2$ emissions of passenger cars in Europe was fleet dieselization. Diesel vehicles currently represent about 50% of new passenger cars sales in Europe and for some countries this figure exceeds 60%.

Fig. 9 shows the excess $CO_2$ emissions compared to certification test ones for the various models employed. Again mod 2 excess emissions appear to slightly increase with time as in the case of Artemis combined. In this case excess emissions are in the order of 15–18% with gasoline excess emissions being higher than those of diesel vehicles contrary to Artemis combined. The picture changes for Mod 1 results. In these datasets an important increasing trend exists towards higher excess $CO_2$. The gap between certification test values and real world emissions starts from 16% in 2006 and reaches up to 25% in 2010 (Fig. 9). Considering the underestimation in 2005–2007 emissions of this model this intense widening trend is probably not realistic. Artemis combined RW results show a more or less steady emissions shortfall between real world operation and certification value in the order of 24%. Mod1 results for years 2008–2010 confirm this excess emissions level.

## 5. Conclusions

Based on the analysis presented it is concluded that during the past decade improvements were achieved in vehicle characteristics that have pushed average passenger car $CO_2$ emissions to lower levels both over certification and real world conditions. A continuous trend towards lower emissions appears to be sustained which is mainly technology driven despite the flexibilities of the European $CO_2$ certification system which probably contribute also in the reductions. There are indications that rolling resistance, powertrain efficiency, mass, idle consumption and also possibly aerodynamic resistances have improved enough in the last decade, so a target of average 130 g $CO_2$/km passenger car emissions for year 2015 seems achievable under the current trends. For certain factors such as rolling resistance and vehicle mass the improvement rates are expected to continue. Others like aerodynamic resistance and idle consumption are difficult to assess. Amongst the vehicle properties average powertrain efficiency can be distinguished as the attribute that showed unexpected increases, contributing significantly in lowering emission levels. This mainly reflects the benefits of the introduction of a series of new technologies in vehicle powertrain, particularly for gasoline vehicles, but may also be attributed, at least partly, to possible gaming practices in the certification procedure. The next few years will reveal whether there is a margin for further increases or if the efficiency of conventional technologies will reach saturation level. In the latter case engine hybridization will be the most likely alternative technology option. However, given current conditions, it is difficult that hybrids will gain a significant share of European market before year 2015. The official adoption of a more stringent goal like the 95 g $CO_2$/km for 2020 will accelerate the introduction of technology options related to vehicle electrification.

Regarding the main questions addressed in this paper it was shown that the benefits in $CO_2$ emissions observed over NEDC are generally reflected over real world driving conditions. Correction factors may be applied to existing emission factors for emissions monitoring and inventorying purposes but they need to be supported by wide experimental campaigns. There are indications that the gap between real world performance and certification test value increases with time. The introduction of the new worldwide harmonised test protocol (WLTP) in the near future is expected to level out these shortfalls. Nonetheless the protocol is still in development-validation phase and considering the necessary phase in period it is unlikely that experimental results for analysis from this procedure will become available before 2015. Currently the certification test-real world $CO_2$ emissions difference was estimated to be between 20 and 25% depending on the calculation assumptions.

An important consideration that also needs to be taken into account in future policy making is the fact that the average new gasoline vehicle emits about the same $CO_2$ over both NEDC and real world conditions as the average new diesel one. Considering the fact that diesel vehicles emit higher levels of $NO_x$ it is possible that the introduction of a diesel vehicle in the passenger car fleet poses higher environmental pressures than a gasoline vehicle would. If this observation stands in the years to come, incentives associated with diesel vehicle purchase in Europe should be re-evaluated.

Finally it is important to consider introducing requirements to report key vehicle characteristics like tyre rolling resistance value, aerodynamic performance etc. of passenger cars. This will allow better monitoring of passenger car generated $CO_2$ emissions and provide more information to consumers.

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